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Ecological Modelling 141 (2001) 241–260

ECOLOGICAL MODELLING

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A process-based hydrology submodel dynamically linked to the plant component of the simulation of production and utilization on rangelands SPUR model

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Received 24 March 2000; received in revised form 20 February 2001; accepted 26 February 2001

Abstract

Due to the great diversity and complex interactions of vegetation, soils, and climate on rangelands, process-based models designed to evaluate rangeland hydrology must include sophisticated plant and animal components that simulate changes in vegetation over space and through time. An infiltration-based submodel similar to that used in WEPP (Stone et al. (1995) USDA-Agri. Res. Service, NSERL Report No. 10, Chap. 4) was dynamically linked to the SPUR2.4 rangeland ecosystem model (Foy et al., Ecol. Model. 118 (1999) 149) to provide the framework for future model enhancement and investigation of the impacts of management on the rangeland ecosystem. Model description and documentation of model modifications are presented for *SPUR 2000*. A sensitivity analysis and initial test of *SPUR 2000* were performed using rainfall simulation plot and micro-watershed data from Idaho sagebrush rangeland. The sensitivity analysis showed improved sensitivity of runoff and erosion to various vegetation parameters. The long-term simulations demonstrated good representation of soil water content, peak standing crop, and evapotranspiration. *SPUR 2000* did a better job of predicting individual thunderstorm runoff events, and estimated 15-year runoff within 12% compared to SPUR2.4, which grossly overestimated runoff. Neither model accurately predicted sediment loss, but predicted values did demonstrate the relatively small amount of erosion that occurs from these rangelands. Neither model could reasonably estimate the snow-driven runoff that dominates these types of western rangelands. Additional research needs to explore the degree of influence that vegetation has on infiltration and runoff and how it varies for different plant communities. Development of specific K_e estimation equations based on this information will strengthen the vegetation–hydrology linkage within the model. © 2001 Elsevier Science B.V. All rights reserved.

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PII: S0304-3800(01)00277-0

Keywords: Rangeland; Hydrology; Model evaluation; Simulation of production and utilization of rangelands; Water erosion prediction project

1. Introduction

For many years, simplistic empirical models (e.g., Universal Soil Loss Equation (USLE), Hydrologic Curve Number technique) have been the primary tools used by both researchers and managers to estimate runoff and erosion from natural and managed systems. Empirical models, often derived from large regional or national databases, lack sufficient flexibility and accuracy to reflect short-term management effects on diverse rangelands and do little to advance our understanding of the complex system interactions controlling site hydrology.

The great diversity and complex interactions of vegetation, soils and climate on rangelands greatly complicates the prediction of management impact on rangeland hydrology. Process-based models that incorporate the important mechanisms involved at different scales of resolution provide a systems approach to expand our understanding of component interaction and offer a structure to explore how management affects the rangeland ecosystem. A variety of process-based, continuous hydrology/erosion models are currently available for different scales of resolution (e.g., TOPMODEL, Beven, 1991; SHE, Abbott et al., 1986; PRMS, Leavesley et al., 1983; HSPF, Bicknell et al., 1993; SLURP, Kite, 1978; THALES, Moore et al., 1988; KINEROS, Woolhiser et al., 1990; YIELD II, Ffolliott and Guertin, 1988; SHAW, Flerchinger and Pierson, 1997; WEPP, Flanagan and Livingston, 1995). Few, however, consider the importance of the interaction between vegetation and hydrology in semiarid and arid regions (Pilgrim et al., 1988), nor can they simulate the long-term variations in vegetation that occur on grazing lands due to abiotic and biotic (e.g., grazing systems) impacts. This limits their ability to address both the short- and long-term impacts of land use and management on rangeland hydrology.

Past research has shown that rangeland plant community type determines a host of parameters that have temporal and spatial impacts on the hydrology of the site. The amount and type of vegetation and litter strongly influences infiltration rates (Blackburn, 1975; Wood and Blackburn, 1981a; Knight et al., 1984; Thurow et al., 1986, 1988; Thurow, 1991). Different plant communities can vary greatly in canopy structure, rooting patterns, consumptive water use, and bare soil exposure, which in turn affect evapotranspirational loss from rangelands (Johnston, 1970; Hsiao and Acevedo, 1974; Beneke, 1976; Branson et al., 1976; Sosebee, 1976; Christie, 1978; Davis and Pase, 1977; Hibbert, 1983; Holmstead, 1989; Hicks et al., 1990). The seasonal dynamics of plant growth and cover have important influences on site hydrology, especially where a small proportion of annual storms have a major impact on soil water content (SWC) and runoff volume (Thurow et al., 1988; Thurow, 1991; Blackburn et al., 1992). The distribution of plant species within the community results in spatial variability in infiltration that greatly influences the hydrology of the site and complicates efforts to model rangeland runoff and erosion (Blackburn, 1975; Johnson and Blackburn, 1989; Blackburn et al., 1992; Pierson et al., 1994).

Sediment production is often related to amount of runoff; and is significantly correlated with vegetation parameters. Even under situations of equal plant cover, range land communities with different growth forms have differing erosion due to the effects of plant species and litter characteristics on kinetic energy and transport capacity (Blackburn, 1975; Wood and Blackburn, 1981b; Blackburn et al., 1982; Knight et al., 1984; McCalla et al., 1984; Thurow et al., 1986; Warren et al., 1986; Pluhar et al., 1987; Thurow et al., 1988; Thurow, 1991). For example, Texas mixed-grass rangelands dominated by bunchgrasses generally have less erosion than those dominated by sod-forming short grasses. The basal characteristics of bunchgrasses coupled with the buildup of litter at the plant base create obstructions to overland flow that stop and hold sediment. Sod-forming or annual grasses generally do not have the basal mass or litter mounding to provide the same level of protection from soil movement.

Herbivores, an inherent part of rangeland communities, are also an important system component because they consume vegetative cover and transpiring leaf tissue and trample soil and standing vegetation. Similarly, long-term grazing can shift the vegetation on a site as a result of herbivores' selective grazing patterns. Over the long term, hydrologic condition is often tied to plant succession patterns and various management practices that influence ecosystem change.

Clearly, process-based models designed to simulate rangeland hydrology must incorporate sophisticated plant and animal components that can track these changes through space and time. Our initial objective was to develop and test a tool that improves the accuracy of runoff estimates for rangelands by enhancing vegetation–soil-hydrology interactions. To accomplish this, we utilized an existing rangeland ecosystem model (Simulation of production and utilization of rangelands, SPUR) that contained pertinent plant and animal components and structural format, and added the infiltration submodel from Water Erosion Prediction Project (WEPP, Flanagan and Livingston, 1995) to upgrade the hydrology component to produce *SPUR 2000*. Our overall goal is to develop an improved, robust model for practical field-level rangeland hydrology evaluation that also establishes a foundation for future research concerning the hydrology–vegetation link on rangelands, and for exploring issues of scale of resolution.

2. History of the model

The SPUR model (Wight and Skiles, 1987), released in 1987 by the USDA-Agricultural Research Service (ARS), was designed to simulate rangeland ecosystem function and response to management. The model is physically based and is comprised of climate, hydrology, plant, animal, and economics modules. Modifications to improve the capability and accuracy of model response were made by Hanson et al. (1992)(SPUR2), Carlson and Thurow (1992, 1996) (SPUR-91), and Foy (1993) (SPUR2.3). These improvements have been combined to produce SPUR2.4 (Foy et al., 1999). Foy et al. state, "there is a pressing need to improve the hydrology component in SPUR2.4 since soil water is such an important driving variable and the production of clean water is so important to human welfare, particularly in semi-arid environments." Carlson and Thurow (1996) found that predicted monthly runoff did not adequately reflect observed monthly runoff; an inherent problem of the curve number (CN) technique that exists in all previous releases of the SPUR model. They noted that the inability to more accurately predict short-term runoff is a weak link between the hydrology and vegetation components in SPUR. Furthermore, the original SPUR hydrology component was essentially unresponsive to management because the CN was pre-set by the user. This value did not change seasonally or annually throughout the model run, except for small adjustments to account for differences in antecedent soil moisture. In order to simulate the effects of management, the user was required to estimate the impact of subsequent management through the choice of a new CN. We have taken SPUR2.4 and replaced the original runoff submodel with the process-based infiltration submodel used in WEPP (Stone et al., 1995). We also modified the evapotranspiration (ET) component, and incorporated the new revised universal soil loss equation (RUSLE; Renard et al., 1997) equations for erosion prediction to compare with the original modified universal soil loss equation (MUSLE; Williams, 1975) technology in SPUR. A large portion of our efforts involved dynamically linking the hydrology and vegetation components. These modifications to the grazing-unit version resulted in *SPUR 2000* (Fig. 1).

3. Model documentation

Modifications made to develop *SPUR 2000* are described below. More detailed descriptions of the SPUR model and individual submodels can be found in Carlson and Thurow, 1992, 1995, 1996.

3.1. Climate

The weather generator chosen for *SPUR 2000* is CLIGEN (Nicks et al., 1995). CLIGEN provides daily inputs of precipitation, maximum and minimum temperature, solar radiation, wind speed and direction, and dew-point temperature based on historical records for numerous sites throughout the USA. CLIGEN also outputs storm parameters that permit development of rainfall intensity distributions required by the infiltration component. A storm disaggregation function developed by Foster and Lane (1987) uses a double exponential function to describe intensity patterns for a single storm utilizing average intensity, ratio of peak-to-average intensity, and time to peak intensity based on amount of precipitation and storm duration. The resulting breakpoint data for the storm event are utilized by the infiltration submodel. *SPUR 2000* is also designed to accept actual breakpoint rainfall data when available.

3.2. Hydrology

3.2.1. Water balance

The soil water balance is maintained on a daily basis using the following equation:

$$\mathrm{SWC} = \mathrm{SWC_i} + (P - I) \pm S - Q - \mathrm{ET} - D,$$

where SWC is the current soil water content, $\mathrm{SWC_i}$ is the initial soil water content, P is total precipitation, I is interception loss, S is snow water content, Q is runoff; ET is evapotranspiration, and D is drainage below the root zone. Soil percolation and snow accumulation and melt routines have not been altered from the original SPUR2.4 submodels.

3.2.2. Evapotranspiration and interception loss

Interception losses were not included in the original SPUR. Interception loss is that portion of rainfall that is intercepted by both standing vegetation (herbaceous and non-woody shrub/tree) and litter, and is based on equations from WEPP Version 97.3:

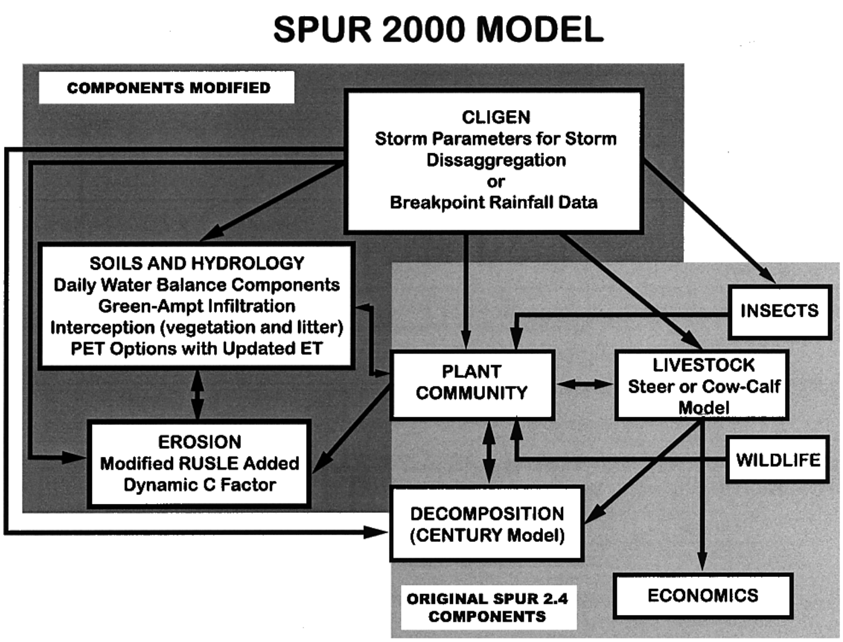

Fig. 1. Basic structure of the *SPUR 2000* model.

$$\text{PLAINT} = \text{CANCOV}*0.001[(0.000627*\text{TLIVE}) - (3.73 \times 10^{-8}*\text{TLIVE}^2)],$$

$$\text{RESINT} = \text{RESCOV}*0.001[(0.000627*\text{LIT}) - (3.73 \times 10^{-8}*\text{LIT}^2)],$$

$$\text{TOTINT} = \text{PLAINT} + \text{RESINT},$$

where PLAINT is plant interception (m), CANCOV is canopy cover (fraction), TLIVE is standing biomass (kg ha^{-1}), RESINT is litter interception (m), RESCOV is litter cover (fraction), LIT is litter biomass (kg ha^{-1}), and TOTINT is total maximum interception (m). TOTINT is adjusted based on actual precipitation. Since intercepted water will likely be evaporated rapidly from a rangeland site, intercepted water in *SPUR 2000* is subtracted from potential evapotranspiration (PET) prior to calculations of potential soil evaporation and plant transpiration.

Carlson and Thurow (1996) found that the ET component of SPUR could not adequately predict the extent of soil evaporation under low cover conditions, and monthly ET tended to be overpredicted during warm wet months. They indicated that calculations of PET with Ritchie's technique (Ritchie, 1972) did not consider wind speed or the effect of standing vegetation. In addition, the input parameter describing mulch cover was a static parameter and did not change throughout the model run. Litter cover input to soil evaporation calculations is now dynamic (i.e., adjusted daily), and additional PET equations were incorporated into the model. Current PET equation options include:

1. Priestley–Taylor (Priestley and Taylor, 1972) – a simplified version of the combination equation and was primarily intended for humid, wet conditions. This was the equation used in the original SPUR model to calculate PET.
2. Penman–FAO (Penman, 1948; Doorenbos and Pruitt, 1977) – a modified Penman combination equation used to estimate reference ET for grass.
3. Penman–Montieth (Montieth, 1965) – the only equation that considers vegetation effects on ET by including aerodynamic and surface resistance terms in the equation.

Wind speed, solar radiation, maximum and minimum temperature, and dew-point temperature are provided on a daily basis by the climate input file (generated or real data) and are used to estimate latent heat of vaporization, saturation vapor pressure, relative humidity, wind function, vapor pressure, vapor pressure deficit, and slope of the saturation vapor pressure curve; elevation is used in the calculation of barometric pressure and psychometric coefficient (Savabi and Williams, 1995; Sharpley and Williams, 1990; Burman and Pochop, 1994). Solar radiation is adjusted for slope and latitude, and algorithms are included to determine net radiation. Vegetation information required by the Penman–Montieth equation (vegetation height, leaf area index) is provided by the plant submodel on a daily basis.

Potential soil evaporation can occur only from the bare areas within a site (litter cover (fraction) provided by plant submodel). Potential plant transpiration is dependent on live leaf area. The model continues to use Ritchie's technique (Ritchie, 1972) to partition soil evaporation and plant transpiration for current conditions. Actual ET is dependent on SWC. Soil evaporation is restricted to the upper soil layers. Transpirational demand is distributed down through the soil using an exponential function to describe root distribution. When upper soil layers become too dry, transpirational demand is transferred to lower soil layers containing roots.

3.2.3. Infiltration

The model is designed to accept either breakpoint precipitation data or CLIGEN-generated storm characteristics as input to the infiltration routine. Intercepted water is removed from the initial breakpoint intervals as needed. The infiltration component, like that found in WEPP, is based on the Green and Ampt (1911) equation:

$$f = K_e*(1 + N_s/F),$$

where f is the infiltration rate, K_e is the effective hydraulic conductivity, N_s is the soil matric potential, and F is the cumulative infiltration. Cumulative infiltration is computed using the technique of Mein and Larson (1973) as presented by Chu (1978) for unsteady rainfall and multiple times to ponding. Rainfall excess is the portion of rainfall which ponds on the surface during a time interval and occurs only when the rainfall rate exceeds the infiltration capacity. An upper limit to water storage is based on the current SWC and pore space. Once the cumulative infiltration exceeds this upper limit, then any additional rainfall becomes excess. The rainfall excess calculated is then reduced by the amount of depression storage available. Maximum depression storage is dependent on site micro-relief and is calculated using the WEPP equation derived from Onstad (1984):

$$S_d = 0.112\mathrm{RRC} + 3.1\mathrm{RRC}^2 - 1.2\mathrm{RRC}*\mathrm{SLOPE},$$

where S_d is depression storage (m), RRC (m) is the relative roughness coefficient, and SLOPE is slope of the site (m/m). Depression storage must be filled before runoff will occur.

Matric potential is determined primarily from soil characteristics (bulk density, sand and clay content, porosity, and SWC). The effective hydraulic conductivity can be input by the user and remain static throughout the run (as recommended by WEPP), or it can be calculated daily based on changes in vegetation (dynamically linked). The following equations are used to estimate the effective hydraulic conductivity on rangelands (Pierson et al., 1996):

For Rill ground cover $< 45\%$ (rill areas defined as areas not directly beneath herbaceous or woody canopy cover):

$$\begin{aligned} K_e = {} & 57.99 - (14.05*\ln \mathrm{CEC}) + (6.2*\mathrm{ROOTOP}) \\ & - (473.39*\mathrm{FBASR}*\mathrm{BASCOV}^2) \\ & + (4.78*\mathrm{FRESI}*\mathrm{RESCOV}^2). \end{aligned}$$

For Rill ground cover $> 45\%$:

$$\begin{aligned} K_e = {} & -14.29 - (3.4*\ln\mathrm{ROOTOP}) \\ & + (37.83*\mathrm{SAND}) + (208.86*\mathrm{PEROM}) \\ & + (398.64*\mathrm{RCC}) - (27.39*\mathrm{FRESI}*\mathrm{RESCOV}) \\ & + (64.14*\mathrm{FBASI}*\mathrm{BASCOV}), \end{aligned}$$

where CEC is cation exchange capacity (meq ml^{-1}), ROOTOP is biomass of roots in top 10 cm (kg m^{-2}), FBASR is the fraction of basal cover in rill areas, BASCOV is total basal cover (fraction), FRESI is the fraction of litter cover in interrill areas, RESCOV is total litter cover (fraction), SAND is proportion of sand in surface soil (fraction), PEROM is the amount of organic matter present in the surface soil (fraction), and FBASI is the fraction of basal cover in interrill areas.

Dry surface soils do not impede infiltration when freezing temperatures persist, while surface SWCs near field capacity can significantly reduce infiltration when frozen. To account for frozen soils, K_e is adjusted based on the following exponential equation relating infiltration rate with water content of frozen soils. The adjustment occurs only when conditions exist for frozen soils, based on inputs from the climate module:

$$K_e = K_e*\exp[-0.025(\theta_a/\theta_{fc})],$$

where K_e is effective hydraulic conductivity, θ_a is current SWC (%), and θ_{fc} is SWC at field capacity (%).

3.2.4. Erosion

The original SPUR model used MUSLE (Williams, 1975) to estimate erosion. All USLE factors were input by the user and did not change throughout the model run. For this initial version of *SPUR 2000*, we chose to compare the most recent USLE technology with USLE/MUSLE before making a decision to incorporate a more process-based erosion component, such as that found in WEPP. Therefore, the current model provides the option of using either MUSLE (runoff ratio factor) or the new RUSLE (rainfall-runoff erosivity factor), with or without a dynamic USLE *C* factor. The calculation of the *C* factor is based on Renard et al. (1997) and calculated on a daily basis:

$$C = \mathrm{CC}*\mathrm{SR}*\mathrm{SC}*\mathrm{PLU},$$

where CC is the canopy cover subfactor, SR is the surface roughness factor, SC is the surface cover factor, and PLU is the prior land use factor.

$$\mathrm{CC} = 1.0 - (\mathrm{CANCOV}*e^{-0.1*\mathrm{CANHGT}}),$$

where CANCOV is the total vegetation canopy cover (fraction) and CANHGT is effective canopy height (ft).

$$\mathrm{SC} = \exp[-0.025*\mathrm{RESCOV}*(0.24/\mathrm{RCC})^{0.08}],$$

$$SR = e^{-0.66*(RCC-0.24)},$$

where RESCOV is ground cover (%) and RCC is surface roughness (in.). The coefficient value of 0.025 was selected to represent rangeland areas dominated by interrill erosion. The PLU factor equation in RUSLE is:

$$PLU = C_f * C_b * \exp[(-c_{ur} * B_{ur}) + (c_{us} * B_{us}/C_f^{cuf})],$$

where C_f is a surface-soil consolidation factor; C_b represents the relative effectiveness of subsurface residue in consolidation; B_{ur} and B_{us} are the mass density of roots and incorporated surface residue in the upper inch of soil, respectively; c_{uf} represents the impact of soil consolidation on the effectiveness of incorporated residue, and c_{ur} and c_{us} are calibration coefficients indicating the impacts of the subsurface residues. Assuming no burial of surface residues and undisturbed soil (no tillage operations), the equation simplifies to:

$$PLU = 0.95 * \exp(-0.00938 * ROOTOP),$$

where ROOTOP is the SPUR equivalent of B_{ur}, representing total root biomass (lb acre^{-1}) in the top 2.5 cm of soil.

The LS, *P*, and *K* factors are set by the user based on tables/figures provided in Renard et al. (1997) (RUSLE) or Carlson and Thurow (1992) (MUSLE). The *P* factor is usually set to one for rangelands to indicate no mechanical practices utilized. In addition, the *SPUR 2000 K* factor can be internally calculated for the user based on the relationship developed for US soils (Renard et al., 1997):

$$K = 7.594 * \{0.0017 + 0.0494 * \exp[-0.5 * ((\log(D_g) + 1.675)/0.6986)^2]\},$$

where D_g (mm) is the geometric mean particle diameter. The *R* factor used in RUSLE is determined based on the average annual total of individual storm EI values in order to characterize annual soil loss for an area. The EI value for an individual storm is the product of total storm energy (100 ft-t acre^{-1}) and the maximum 30 min storm intensity (in h^{-1}). Because *SPUR 2000* uses a daily time step, erosion estimates for an individual storm are based on the actual EI value for that storm. The energy and intensity parameters needed are calculated within the new infiltration submodel from information provided by either breakpoint data or storm disaggregation.

3.3. Hydrology–vegetation links

Plant growth in the SPUR model is responsive to temperature, soil water and nitrogen availability, seasonality, and to herbage removal and trampling by animals. These controlling parameters are updated on a daily basis, allowing the model to track the short-term vegetation response. In addition to seasonal fluctuations in plant growth, the proportion of individual species can change over time depending on natural disturbances or management impacts. Therefore, changes in the plant community as they affect cover, height and biomass attributes are also simulated. A significant effort was made to dynamically integrate the hydrology component with the vegetation component by substituting static parameters (user-set values that did not change during the model simulation) with comparable parameters in SPUR that are continuously updated throughout the model run in response to season, climate, management, and competitive interactions between plant species for soil water and nutrients. The plant growth submodel and grazing interface within SPUR2.4 were linked to the hydrology component by utilizing basic relationships (Arnold et al., 1995) developed to:

(1) Relate biomass to canopy height (used in the Penman–Montieth equation and RUSLE). The projected areas of herbaceous and woody plants are calculated based on plant diameter, geometric plant shape, and population size, and the effective canopy height is determined based on different species' heights and their projected areas:

$$TOTPAI = TPAI + SPAI + GPAI,$$

$$CANHGT = (GHGT * GPAI + SHGT * SPAI + THGT * TPAI)/TOTPAI,$$

where TOTPAI is total projected plant area, TPAI is the plant area of trees, SPAI is the plant area of shrubs, GPAI is the plant area of herbaceous vegetation, CANHGT is effective canopy height (m), and GHGT, SHGT, and THGT are the heights of herbaceous plants, shrubs and trees, respectively. In the current version, only the projected areas of herbaceous plants change on a daily basis; shrub and tree area are presumed to remain fixed over the length of the model run, as is currently done in WEPP.

(2) Relate litter and standing vegetation biomass to cover (infiltration and erosion submodels)

$$\text{RESCOV} = 1.0 - \exp(-\text{RESCOF} * \text{ALIT}),$$

$$\text{CANCOV} = 1.0 - \exp(-\text{CANCOF} * \text{TOTSTD}),$$

where RESCOV is litter cover, RESCOF is a shaping parameter, ALIT is biomass of litter (kg m^{-2}), CANCOV is canopy cover, CANCOF is a shaping parameter, and TOTSTD is weight of standing vegetation (kg m^{-2}).

(3) Relate basal cover to canopy cover (infiltration submodel)

$$\text{BASCOV} = 0.429 * \text{CANCOV}.$$

(4) Utilize live and dead root biomass to determine surface rooting characteristics (infiltration and erosion submodels). Biomass of live and dead roots is distributed through the soil profile using an exponential relationship in order to calculate the root biomass in the upper 10 cm of soil.

4. Initial model evaluation

4.1. Testing procedure

Once the initial modifications to the model were complete, *SPUR 2000* was compared to SPUR2.4 to assure that the new framework represented a positive step forward. A sensitivity analysis was performed based on data from large rainfall simulation plots located in Idaho. Key parameters were isolated and the new vegetation–hydrology linkage was compared to sensitivity analysis results for the SPUR2.4 model. An initial verification showed that the basic components of SPUR remained intact and performed in a similar manner to SPUR2.4. Then we tested the model to: (1) evaluate the plant growth component's ability to accurately reflect short- and long-term vegetation response, (2) compare hydrology response between the two models in relation to the vegetation links, and (3) identify problems that will need to be addressed during the next phase of development. This model testing was conducted using long-term data from a local micro-watershed (1.3 ha). Inputs were initialized using actual data when available. Inputs based on actual data were not adjusted. No attempt was made to optimize model output for these preliminary tests. The long term runs were calibrated to the first three years of peak standing crop (PSC) data by adjusting pertinent plant input parameters, and then vegetation response, ET, and SWC were compared with actual data from different periods throughout the long term run (23 year). Actual climate data for the site (or sites within close proximity) were utilized in this simulation along with CLIGEN-generated storm parameters to disaggregate individual storm events. Actual breakpoint rainfall data were used as inputs for a separate 15-year simulation run to test only the infiltration and erosion submodels. Long-term simulated runoff and erosion were compared with SPUR2.4 output. The same inputs were utilized for both models, with slight adjustment to several plant parameters to assure very similar vegetation amounts and response over time. Outputs were compared for a range of SPUR2.4 CNs.

4.2. Study area

The Nancy Gulch micro-watershed used as the initial test site for the model is located within the Reynolds Creek Experimental Watershed situated in the Owyhee Mountains of southwestern Idaho (43.6°N, −116.75°W). Average annual precipitation is 280 mm. Elevation of the site is 1400 m with 8% slope. Soils are fine, mesic, montmorillonitic Xerollic Durargids (Gariper silt loam) with varying degrees of hardpan formation. Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle and Young) is the dominant shrub species at Nancy Gulch. Common grass species include Sandberg bluegrass (*Poa sandbergii* Vasey) and bottlebrush squirreltail (*Elymus elymoides* (RAF.) Swezey). Perennial forbs make up a small percentage of total vegetation in most years. Green biomass averages 500–1000 kg ha^{-1}, with $\approx 20\%$ shrub cover and 5% herbaceous cover. Ground is covered by rocks (15%), cryptogams (25%), litter (25%) and basal vegetation (10%). The micro-watershed is outfitted with a weir that continuously records runoff volume and sediment discharge. Actual climate data from the site (or a nearby site for wind, solar radiation, and dewpoint temperature) were used to develop the required climate input files. PSC, soil moisture data (neutron probe), soil loss, and ET (Bowen ratio) data used to evaluate the model were available for only portions of the simulation period. Large simulation rainfall-runoff plots located near the micro-watershed are 32.6 m^2. These natural (undisturbed) plots were used to test model sensitivity.

5. Evaluation results

5.1. Sensitivity analysis

Over forty input parameters were evaluated for their effect on amount of runoff; effective hydraulic conductivity, matric potential, and erosion (Table 1). A baseline run was made using actual plot data. Input parameters were then varied $\pm$ 10 and $\pm$50% to evaluate sensitivity. A normalized sensitivity parameter was calculated for each parameter for both the 10 and 50% changes using the equation:

$$S = [(O_H - O_L)/O_A]/[(I_H - I_L)/I_A],$$

where I_L and I_H are the least and greatest values of the inputs used, I_A is the average of the inputs, O_L and O_H are the corresponding output for the two input values, and O_A is the average of the two outputs. In this way, sensitivities can be compared for input parameters with different orders of magnitude (Nearing et al., 1990). Because the sensitivity parameter (S) is a function of the chosen input range, the two levels of input parameter changes (10 and 50%) provide more insight into the effect on model output.

SWC at field capacity had the greatest influence on amount of runoff (Table 2). Amount of runoff was also sensitive to the random roughness coefficient and proportion of sand in the surface soil. Various plant attributes and cover factors influenced runoff; but to a lesser degree. Sediment was most affected by the rooting depth, since this factor is used to calculate the root biomass at the surface. The amount of surface roots (used in calculating the PLU subfactor) was an important parameter in the estimation of the RUSLE C factor. Vegetation characteristics (amount of litter, dead and live root biomass) also influenced erosion as they impacted the calculation of the RUSLE C factor. K_e was greatly influenced by the amount of sand present in the surface soil, and also by the random roughness coefficient. Vegetation parameters had greater impact on K_e at 10% change then at 50% change, which was due primarily to moving from one predictive equation (dependent on rill cover) to another. Matric potential, as expected, was most influenced by soil characteristics (SWC at field capacity and amount of sand).

5.2. Long-term micro-watershed runs

Correspondence between simulated and measured PSC for the four functional groups is shown in Fig. 2. For the eight years with PSC data available, the predicted PSC of sagebrush was within the measured range four out of eight years, and was very close to the lower range in two additional years. Years with below normal sagebrush production were not well simulated by the model. PSC of bluegrass was within the measured range in three out of eight years, but in only 1 year did simulated PSC differ from measured PSC by more than 50 kg ha^{-1}. PSC of squirreltail and other mid-sized bunchgrasses was accurately predicted for all but one year. PSC of forbs was difficult to predict, but was estimated within 100 kg ha^{-1} in all but two years, when estimated production was much greater than actual production. Over the 23-year run, the community remained stable but was responsive to years with differing precipitation amounts and patterns.

Measured SWC was available for the Nancy Gulch site starting in 1976. Simulated total profile SWC closely matched the temporal pattern seen in the measured water content (Fig. 3a) over an

Table 1
SPUR 2000 input parameters used to test the sensitivity of the hydrology submodel

Input	Definition	Model units	Base value
ALIT	Litter biomass	g m^{-2}	287
AVE HGT	Average height of plant	m	1.0, 0.18, 0.35, 0.3[a]
BASI	Basal cover in interrill areas	fraction	0.104
BASR	Basal cover in rill areas	fraction	0.115
BDEN	Bulk density	g cm^{-3}	1.24, 1.42[b]
CANCOF	Shaping coefficient for vegetation	–	1.2
CEC	Cation exchange capacity	meq ml^{-1}	26, 30.6[b]
CLAY	Proportion of clay particles	fraction	0.194, 0.259[b]
CONA	Evaporation parameter	in. $day^{-0.5}$	0.178
CRYI	Cryptogam cover in interrill areas	fraction	0.168
CRYR	Cryptogam cover in rill areas	fraction	0.203
DIAM	Plant species diameter	m	0.75,.05, 0.20, 0.15[a]
DROOTS	Dead root biomass	g m^{-2}	360
MAX HGT	Maximum height of plant	m	1.5, 0.2, 0.8, 0.5[a]
P1	Maximum net photosynthetic rate	(mg dm^{-1})h^{-1}	5.5, 13, 14, 12[a]
P16	Phytomass to LAI conversion	–	0.03, 0.015, 0.02, 0.03[a]
P3	Maximum temperature for plant	C°	38, 33, 35, 33[a]
P4	Optimum temperature for plant	C°	20, 15, 17, 17[a]
P6	Water potential for $\frac{1}{2}$ maximum Ps	−bars	35, 11, 9, 7[a]
P9	Root-to-shoot ratio	ratio	6, 3, 5, 2.5[a]
PERRF	Rock fragments in soil	fraction	0.19, 0.15[b]
PERROM	Soil organic carbon	fraction	0.0128, 0.0093[b]
PHTYM1	Standing live biomass	g m^{-2}	33.3, 8.2, 0.7, 1.5[a]
PHTYM2	Live root biomass	g m^{-2}	266.3, 64.2, 33.9, 26.6[a]
PHTYM4	Standing dead biomass	g m^{-2}	80.9, 6.8, 0.8, 1.8[a]
PNS1	Decomposition rate of dead roots	proportion	0.0035
PNS2	Decomposition rate of litter	proportion	0.018
POP	Number of plants along 100 m	–	30, 250, 80, 250[a]
RD	Rooting depth	in.	36.23
RESCOF	Shaping coefficient for litter	–	1.0
RESI	Litter cover in interrill areas	fraction	0.201
RESR	Litter cover in rill areas	fraction	0.277
ROKI	Rock cover in interrill areas	fraction	0.140
ROKR	Rock cover in rill areas	fraction	0.145
RRC	Random roughness coefficient	m	0.0102
SAND	Proportion of sand particles	fraction	0.299, 0.240[b]
SLOPE	Slope of the site	foot $foot^{-1}$	0.063
SLSC	Saturated hydraulic conductivity	in. h^{-1}	0.176, 0.115[c]
SM0	Porosity of the soil layer	fraction	0.508, 0.44[b]
SM15	SWC at wilting point	fraction	0.12, 0.153[b]
SM3	SWC at field capacity	fraction	0.255, 0.29[b]

[a] Values for *Artemisia*, *Poa*, *Sitantion*, and forbs, respectively.
[b] Values for the first and second soil layer, respectively.
[c] Values for the third and fourth soil layers, respectively.

11-year period. Simulated water content underestimated measured water content in only two years. For the years with actual PSC data (1976–1980), there was a close correspondence between measured and simulated SWC. Measured SWC in the top 30 cm was also closely estimated by the model (Fig. 3b), but the model demonstrated more rapid dry-down than reflected in the measured data. The surface soil moisture is an important controlling factor for plant growth responses and decomposition, so the ability to accurately simulate surface soil water is an important capability of the SPUR model.

ET measurements over a 4-month period were made on the watershed in 1991. While there was no vegetation or cover data available for that period, the predicted vegetation biomass and cover were assumed to accurately reflect what occurred on the site so that the three different potential/reference ET (PET) equations could be evaluated (Table 3). Daily ET estimates made by the Penman–Montieth equation never exceeded 0.17 mm during the growing season, and measured daily ET never exceeded 0.16 mm. However, because they do not consider the effects of vegetation cover, daily ET estimates made by the other two equations exceeded 0.22 mm on warm days with greater SWCs. ET predicted using three different equations to estimate PET provided similar estimates of 10-day measured ET. Monthly measured ET was estimated slightly better using Penman–Montieth than the other equations. Total simulated ET estimates for the 4-month period were $\approx 20\%$ lower than measured, but this was primarily due to soil water availability as predicted by the model. By mid-June, the soils had become quite dry, so that the ET demand predicted by the model could no longer be met because the simulated soils were too dry.

Breakpoint precipitation (incremental intensity data for individual storms) for the watershed was available from 1981 to 1995. Vegetation information from the 23-year simulation of the Nancy Gulch site was used to initialize the model for a 15-year run to evaluate the infiltration component. The original model (SPUR2.4) was also run with the same or very similar input parameters to compare the differences in runoff between the Green and Ampt submodel and the CN. *SPUR 2000* runoff during May–September was compared to SPUR2.4 at four different CNs (Table

Table 2
Sensitivity (S) of runoff, erosion, K_e and matric potential to selected input parameters[a]

Input	Runoff		Erosion		K_e		Matric potential	
	10%	50%	10%	50%	10%	50%	10%	50%
Rooting depth (RD)	−0.180	−0.333	**2.548**	**1.831**	0.270	0.303	−0.012	−0.014
Surface roughness (RRC)	−0.525	−0.689	−0.438	−0.371	0.442	0.446	0	0
Soil porosity (SM0)	0.180	−0.304	0	0	0	0	−0.260	0.134
Field capacity water content (SM3)	**1.229**	**1.271**	0.088	0.011	0	0	**−1.239**	**−0.496**
Soil organic carbon (PERROM)	−0.180	−0.387	0	0	0.293	0.297	0.309	0.015
Clay content (CLAY)	−0.180	−0.328	0.123	0.122	0	0	0.282	0.286
Sand content (SAND)	−0.525	−0.611	−0.158	−0.165	**1.244**	**1.237**	**−0.918**	**−0.859**
Litter cover interrills (RESI)	0.000	0.208	0	0	−0.044	−0.155	0	0
Litter cover rills (RESR)	−0.180	−0.208	0	0	0.183	0.148	0	0
Cryptogam cover rills (CRYR)	−0.669	−0.134	0	0	0.449	0.102	0	0
Litter shaping coefficient (RESCOF)	−0.328	0.095	**−1.010**	**−0.943**	0.337	−0.008	0	0
Vegetation shaping coefficient(CANCOF)	0.000	−0.110	−0.228	−0.243	0.206	0.130	0	0
Litter biomass (ALIT)	−0.328	0.095	**−1.010**	**−0.940**	0.336	−0.008	0	0
Dead root biomass (DROOTS)	0.180	0.246	**−1.696**	**−1.391**	−0.179	−0.190	0	0
Standing live biomass (PHYTM1)	0.000	−0.036	−0.088	0.238	0.073	0.050	−0.022	−0.016
Live root biomass (PHYTM2)	0.180	0.246	**−1.828**	**−1.446**	−0.187	−0.164	0.002	−0.007

[a] Results are presented for model inputs altered 10% and 50% from their baseline values. Bolded values indicate the input parameters that have the greatest effect on the response variables. ($S=[(O_H-O_L)/O_A]/[(I_H-I_L/I_A]$, where I and O are the greatest (H), least (L), and average (A) values of parameter input and corresponding response output, respectively).

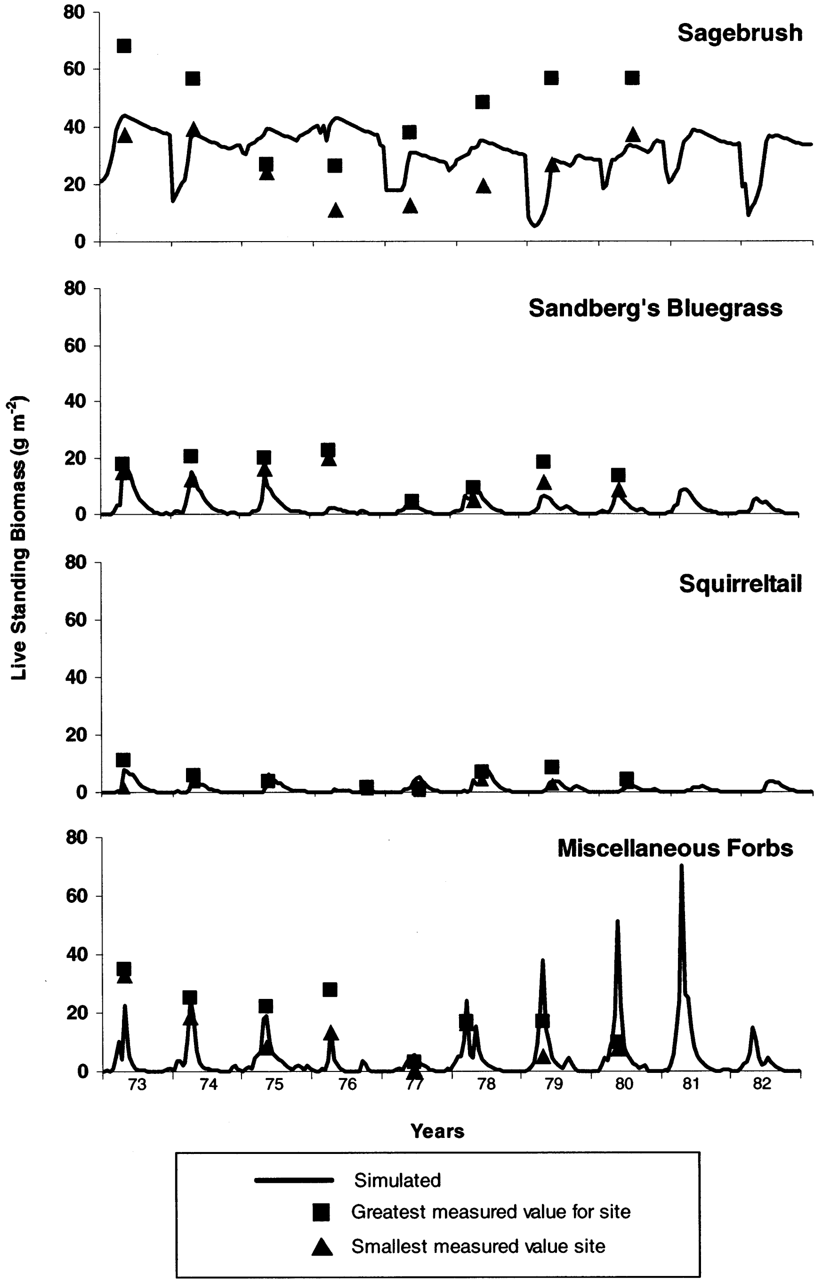

Fig. 2. Ten-year measured and simulated live plant PSC (g m^{-2}) at Nancy Gulch microwatershed for: (a) Wyoming big sagebrush, (b) Sandberg bluegrass, (c) bottlebrush squirreltail, and (d) miscellaneous perennial forbs. High and low measured PSC for each year are presented to indicate the variability in measured data.

4). These CNs represent the range of values that would be selected by an experienced user for this sagebrush range site, based on information (e.g., vegetation cover type, ground cover, and hydrologic soil group) provided in the user guide (Carlson and Thurow, 1992). Only four small thunderstorm runoff events occurred during the 15-year period. *SPUR 2000* closely predicted two of these events, and the other two were less than 0.1 mm. For SPUR2.4 (CN = 60), none of the actual events were predicted, but two additional events that did not occur were predicted. With a CN of 75, SPUR2.4 accurately predicted the largest event (June 1982), but over-estimated two of the other actual events. In addition, it also predicted runoff from six additional events that did not occur. Total thunderstorm runoff for the 15-year period was 0.38 mm, and *SPUR 2000* predicted total runoff of 0.43 mm. In order to predict the largest event that actually occurred, SPUR2.4 (CN = 75) predicted total runoff of 10.7 mm, substantially greater than measured runoff. Of the 22 winter events that occurred, measured runoff ranged from 0.3 to 8.7 mm. *SPUR 2000* predicted only one of these events, while SPUR2.4 (CN = 75) predicted six. However, neither model accurately estimated the amount of runoff for the events predicted.

Measured erosion from 1981 to 1984 averaged 8.8 kg ha^{-1} year^{-1}. *SPUR 2000* (RUSLE) predicted 2.2 kg ha^{-1} year^{-1} for the same period. SPUR2.4 predicted erosion ranging from 12.5 to 170.2 kg ha^{-1} year^{-1} depending on the CN selected. Neither model accurately predicted the

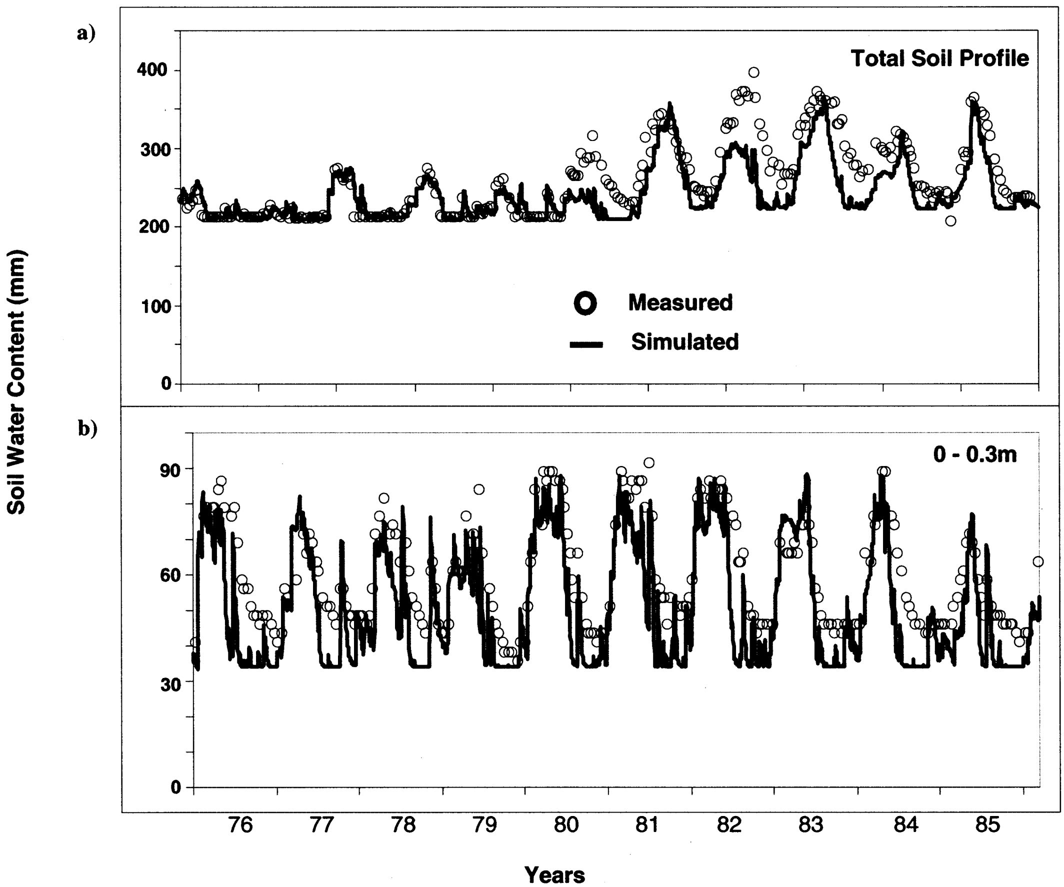

Fig. 3. Measured and simulated SWC (mm) at the Nancy Gulch microwatershed from 1976 to 1986 in: (a) the entire soil profile, and (b) the 0–0.3 m surface layer.

Table 3
Measured and simulated ET from April through July 1991 for (a) 10-day periods, (b) monthly periods, and (c) the entire season[a]

Periods	Measured ET (mm)	Simulated ET (mm)		
		Penman–Montieth	Penman FAO–24	Priestley–Taylor
(a) 10 day				
April 5–April 14	14.33	9.65	12.67	12.57
April 15–April 24	14.16	15.37	16.41	16.79
April 25–May 4	15.39	17.45	14.63	15.06
May 4–May 13	18.56	13.36	10.69	12.93
May 14–May 23	25.52	22.15	22.96	25.43
May 24–June 2	23.02	26.16	22.91	22.20
June 3–June 12	15.72	10.36	10.52	8.10
June 13–June 22	8.33	0.69	1.09	0.58
June 23–July 2	13.87	9.68	9.88	10.24
July 2–July 7	4.97	0.91	0.81	0.38
		$R^2 = 0.84$	$R^2 = 0.84$	$R^2 = 0.85$
(b) Monthly				
April (partial)	39.34	34.11	38.74	39.90
May	64.63	59.44	54.97	59.21
June	41.42	28.32	25.65	22.76
July (partial)	8.48	3.91	3.23	2.41
		$R^2 = 0.97$	$R^2 = 0.92$	$R^2 = 0.89$
(c) Seasonal				
April 5–July 7	153.87	125.78	122.59	124.28

[a] Simulated ET is presented for the three different PET equation options in *SPUR 2000*, and their relation to the measured data (R^2).

actual amount of soil loss. The *SPUR 2000* model under-predicted erosion by four-fold, and SPUR2.4 (MUSLE) over-predicted erosion by up to 21 times.

The effective hydraulic conductivity is the primary way in which vegetation influence on infiltration is incorporated into the infiltration submodel. K_e is quite dynamic throughout the 15-year simulation and is responsive to vegetation and frozen soil conditions (Fig. 4). K_e decreases over the growing season as plant biomass increases. This is primarily due to the negative correlation between K_e and basal cover and litter cover represented by the regression equations used to predict baseline rangeland K_e. However, when production increases in response to greater precipitation such that rill cover is greater than 45% (e.g., the last year of the simulation run), the regression equations do predict higher K_e values during this time in response to greater vegetation biomass and cover. The dynamic RUSLE C factor is seasonally responsive to vegetation and annually as well (Fig. 5). Greater values for RUSLE C are associated with non-growing periods when less standing vegetation is available to dissipate raindrop impacts, and less litter and ground cover are present to act as barriers to water movement. Calculated RUSLE C factor values are consistent with published estimates for similar sites (Wischmeier and Smith, 1978).

6. Discussion

In the original SPUR model (and subsequent releases), amount of runoff was essentially insensitive to plant input parameters (Carlson and Thurow, 1992) and the plant and hydrology components were too independent (MacNeil et al., 1987). The *SPUR 2000* sensitivity analysis demonstrates the hydrology submodel's improved link to the plant component. Various plant biomass and cover attributes significantly affect rangeland infiltration, and the model is now capable of incorporating this influence into simulated infiltration processes. However, the relationships from WEPP relating cover and biomass have not been validated and need further evaluation. Likewise, the degree of influence that vegetation has and how it varies for different plant communities needs further study through continued model testing and enhancement.

SPUR 2000's strength is its ability to track vegetation production and trend over the long term, and incorporate the effects of management within the simulated plant community. This capability to adequately predict seasonal plant growth and compositional changes is a vital link to rangeland hydrology. However, the plant growth component was originally developed for grassland communities. While a determinant-type growth pattern for shrubs can be generated by setting specific parameters outside the "ecological" ranges (Carlson and Thurow, 1992), plant growth responses represent herbaceous vegetation. The model contains no algorithms for light attenuation, woody growth or respiration of woody tissue, etc. Inclusion of a true shrub component would improve use of the model for rangeland decision-making where shrubs exist.

The Green–Ampt infiltration model seemed appropriate for this application, and better runoff estimates can be expected as we improve our ability to estimate K_e. The original WEPP equations designed to predict K_e were intended only to estimate a baseline optimal value for rangelands, and were not intended to be dynamic (e.g., no change in response to seasonal changes in vegetation cover). Therefore, the regression equations, based on 34 locations throughout the western USA. (Pierson et al., 1996), incorporated correlations with cover characteristics that were not con-

Table 4
Measured and simulated runoff (mm) for the Nancy Gulch microwatershed[a]

Event	Runoff (mm)					
	Measured	*SPUR 2000*	SPUR2.4			
			CN = 60	CN = 65	CN = 70	CN = 75
Actual rainfall events						
June 1982	0.254	0.229	0	0	0	0.254
June 1983	0.076	0	0	0	0.254	0.762
June 1984	0.025	0.203	0	0	0.508	1.270
June 1992	0.025	0	0	0	0	0
Total	0.381	0.432	0	0	0.762	2.286
Predicted rainfall events (events did not actually occur)						
May 1981	0	0	0	0	0	0.254
May 1983	0	0	0.254	0.254	1.016	2.286
May 1987	0	0	0	0.254	0.254	1.270
May 1993	0	0	0	0.254	0.508	1.524
June 1993	0	0	0	0	0	0.254
May 1995	0	0	0.254	0.508	1.524	2.794
Total	0.381	0.432	0.508	1.270	4.064	10.668

[a] All events occurring during the period May to September (primarily thunderstorms) are presented for 1981–1995. Additional events not actually occurring but predicted by the models are also presented. Predicted runoff for the SPUR2.4 model is shown for CNs set at 60, 65, 70, and 75.

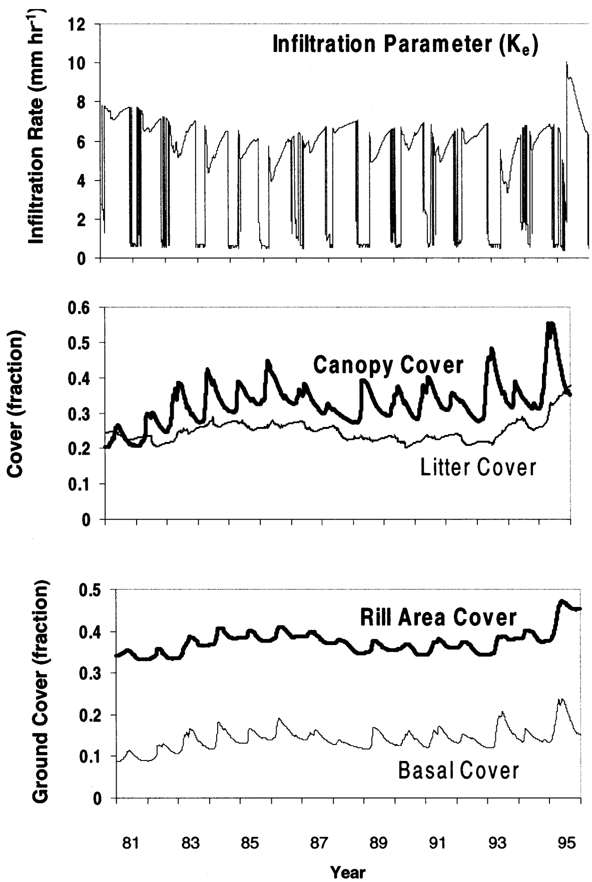

Fig. 4. Fifteen-year effective hydraulic conductivity (K_e, mm h^{-1}) and its relationship to simulated response of vegetation parameters such as canopy cover (fraction), litter cover (fraction), rill area cover (fraction), and basal cover (fraction).

ceptually correct with regards to spatial and temporal fluctuations. The dynamic K_e in *SPUR 2000* provides the foundation for increasing our understanding of the vegetation–hydrology link on range lands, and provides a logical next step of testing and improving predictive K_e equations. Additionally, we need to improve simulation of hydrologic processes during winter periods by incorporating technology to address frozen soils and rain-on-snow events, which dominate the runoff events in these types of northwestern rangelands.

A dynamic RUSLE *C* factor was included in the model to permit *SPUR 2000* to more accurately assess the impacts of management (as they alter vegetation) on sediment produced from a site, compared to the static USLE factor used in the original model. However, RUSLE under-estimated the amount of erosion for the micro-watershed. The sensitivity analysis revealed that erosion was particularly sensitive to the amount of surface roots, due to the prior land use coefficient in the RUSLE *C* factor. The amount of surface roots is difficult to measure on rangelands and little root data exist. Therefore, accuracy of the estimated values of root biomass calculated by the plant component of SPUR (and corresponding values of the PLU subfactor) could not be evaluated, but RUSLE *C* factor values calculated within *SPUR 2000* were consistent with those found in the

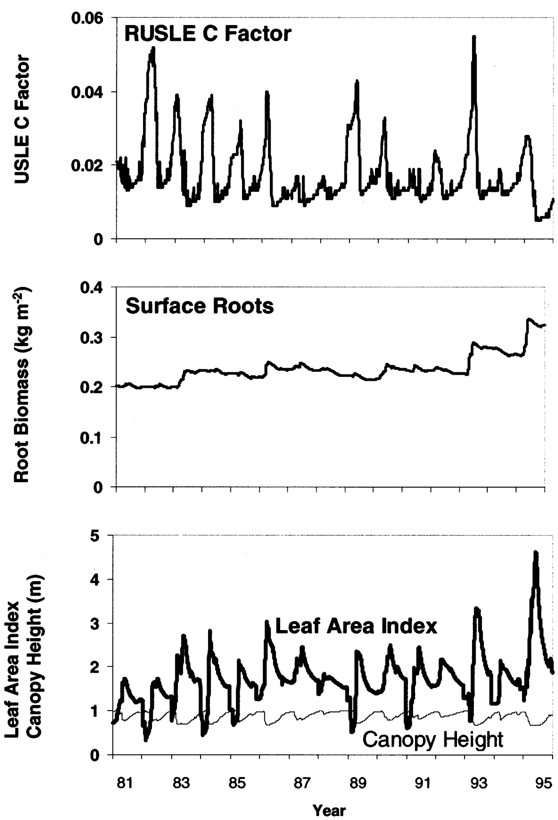

Fig. 5. Fifteen-year RUSLE *C* factor and its relationship to simulated response of vegetation parameters such as biomass of surface roots (kg m^{-2}), canopy height (m), and leaf area index.

literature for similar sites. The uncertainty associated with *SPUR 2000* root biomass estimates, coupled with the sensitivity of erosion estimates to surface root biomass, is problematic. Therefore, special care is needed to initialize the model with respect to root biomass to obtain better estimates of the RUSLE *C* factor using the current subfactor equations. Further research is needed to examine the RUSLE model's seemingly over-sensitivity to root biomass and explore if perhaps the PLU sub factor also represents the influence of additional factors on erosion.

The original SPUR model utilized the USLE technology, and this site-level model now has improved components to that technology. However, it should be noted that erosion models such as RUSLE cannot benefit from the improved infiltration and runoff estimations in *SPUR 2000* because they do not utilize runoff amount or characteristics in their prediction algorithms. Furthermore, RUSLE was designed primarily to predict average annual soil loss, and the algorithms were not developed for prediction of soil loss from individual storm events. Incorporation of overland flow and sediment detachment/deposition algorithms such as those found in the WEPP model should improve short-term erosion predictions at the landscape-scale and the response to management.

Soil water and ET were adequately simulated within *SPUR 2000*. The PET options provide similar ET estimates, but the Penman–Montieth equation may provide slightly better estimates, especially for more arid environments (Allen et al., 1989). Differences between measured and modeled ET and soil moisture are difficult to assess without corresponding vegetation data. Some differences may have been due to: (1) the model assumption of zero water content at -50 bars, (2) a pre-set rooting depth that is not responsive to water demand, (3) lack of seasonal calibration for model runs, therefore some species may not have been turning on/off at correct times according to temperature and soil moisture, (4) difficulty of simulating the growth response and physiology of shrubs and annuals, and (5) accessibility by shrubs or deeper rooted species to soil below the user-set rooting depth.

7. Implications

(a) *SPUR 2000* provided improved runoff estimation and a stronger, dynamic link to vegetation than the original SPUR utilizing the CN technique. The model demonstrated an improved ability to predict individual thunderstorm events from this semiarid northwest rangeland. Although *SPUR 2000* under-estimated erosion at the micro-watershed scale, the erosion submodel is more responsive to management with regard to the dynamic RUSLE *C* factor. More work is needed to improve our ability to accurately predict soil loss on rangelands and its affect on long-term soil productivity and stability of plant community dynamics. For example, there is currently no mechanism in *SPUR 2000* to account for soil loss in relation to depth of soil profile or nutrient availability stored within the surface horizon. These types of relationships need to be addressed to reflect impacts of management activity.

(b) Available data suggest that two K_e estimation equations (based on rill ground cover) are not adequate to estimate the influence of vegetation on infiltration for the diversity of conditions found on rangelands throughout the USA. Future improvements to the infiltration submodel will involve revised and expanded K_e estimation equations. The foundation within the model now exists to proceed to this next step.

(c) Additional testing on varied sites is needed to increase understanding of the vegetation–hydrology relationship and how it differs between plant communities. The model provides the framework for a systems approach to explore these interactions.

(d) Additional modifications to incorporate snow processes, frozen soils, process-based ET, and overland flow effects on sediment detachment/deposition will improve our capability to model vegetation–hydrology relationships on rangelands at different scales of resolution.

Acknowledgements

Research was supported in part by the United States Department of Agriculture, Natural Resources Conservation Service.

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